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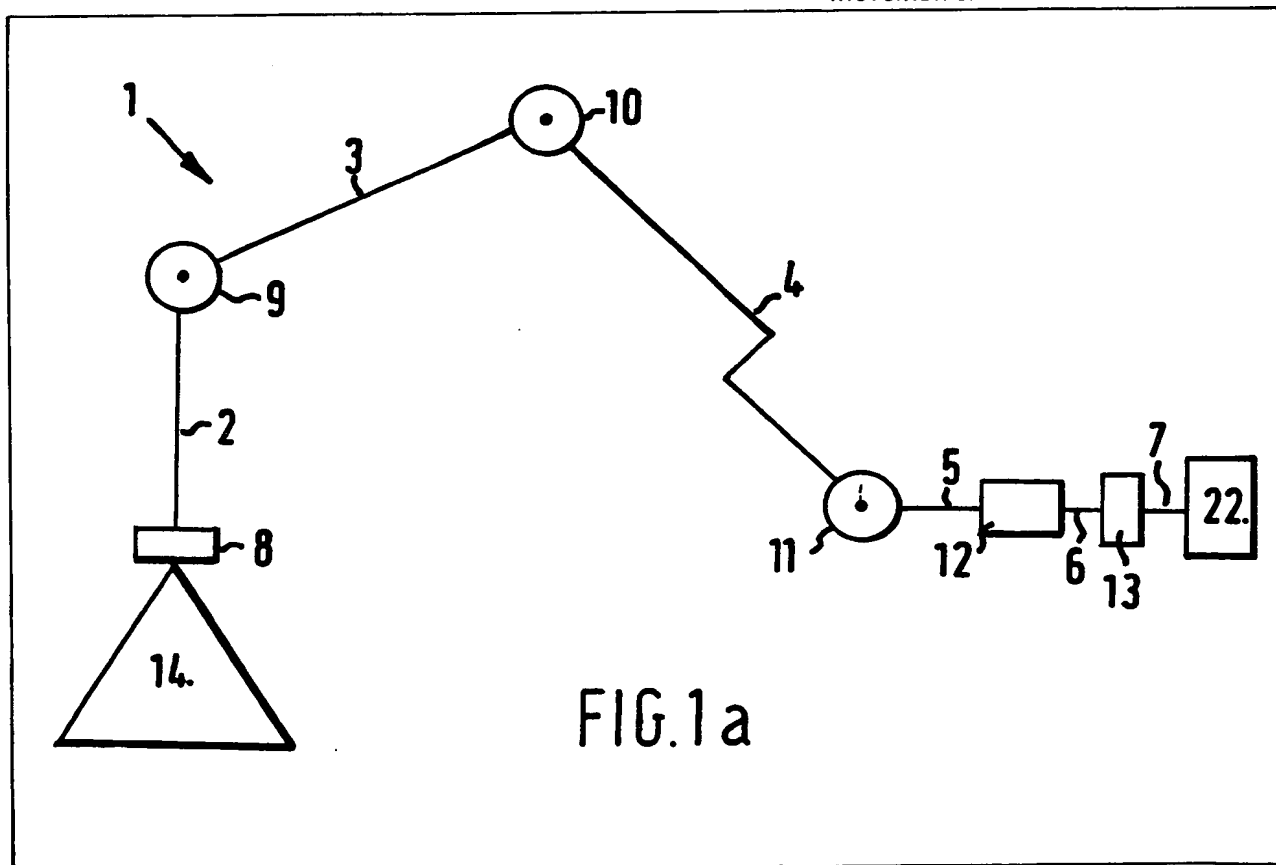
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(71) Applicants
Custom Microdesign
Limited
(Great Britain),
14 High Street,
Poole,
Dorset BH15 1BP
(72) Inventors
Lenard John Maynard
Alan Gordon Witts

(74) Agents
Hughes Clark Andrews
and Byrne,
63 Lincoln's Inn Fields,
London WC2A 3JU

(54) **Digital movement controller for automatic multi-axis machines**

(57) In a multi-axis machine tool, welder, sprayer, or robot, the spatial position of the machine depends upon the contemporaneous positions of its several axes. Each axis (8 to 13) is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines the distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move to a required direction and velocity during the next time period until the axis has reached its final target position. A central controller supplies target positions to the several control modules through a common data highway to bring about required axis movements.
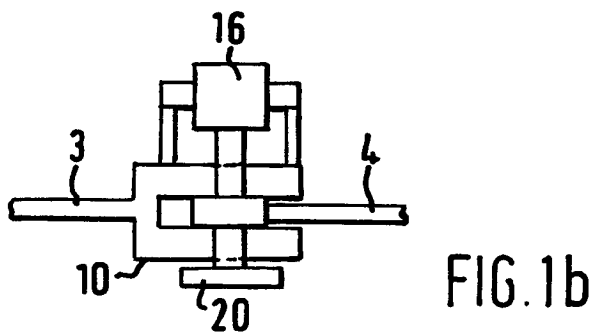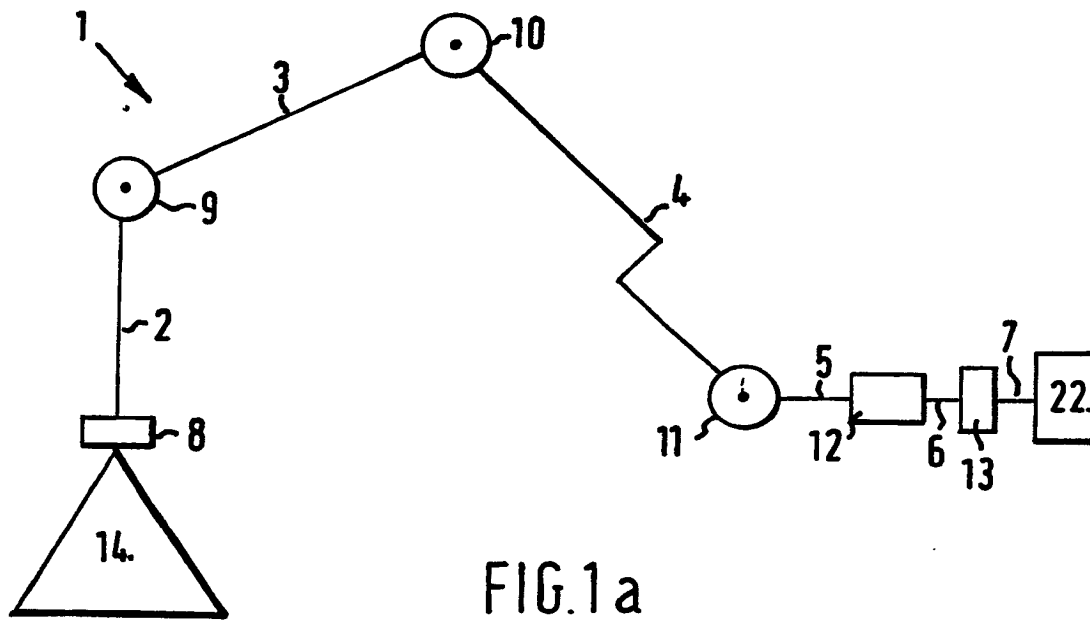
FIG.1a
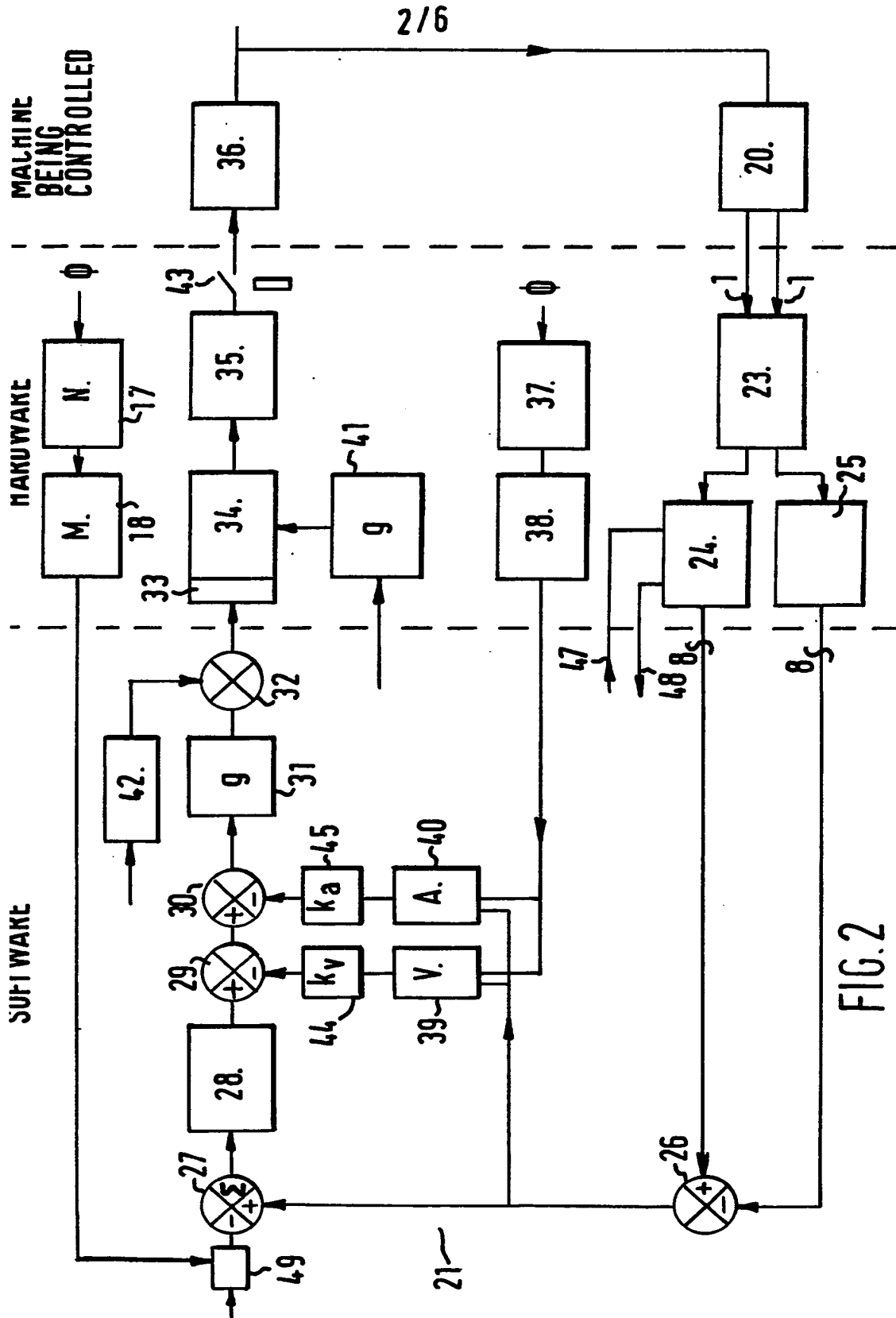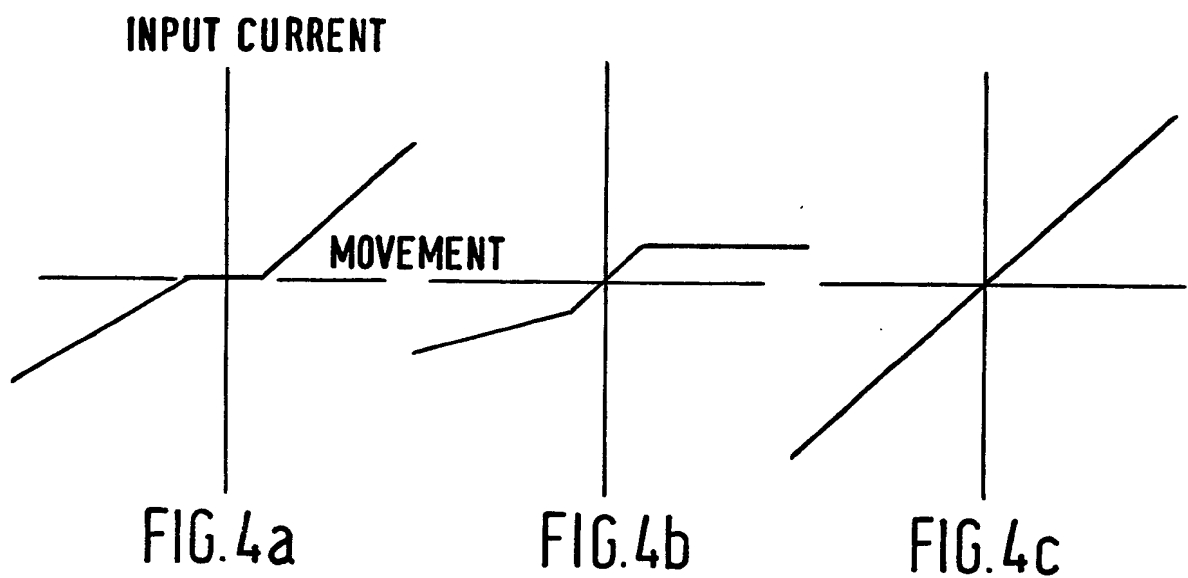
FIG.1a

FIG.1b

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MACHINE BEING CONTROLLED

HARDWARE

SOFTWARE

FIG.2

2102590

FIG.3a

CLOCKWISE
SIGNAL

COUNTER-CLOCKWISE
SIGNAL

FIG.3b

INPUT CURRENT

MOVEMENT

FIG.4a   FIG.4b   FIG.4c

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FIG.5

FIG.8

FIG.6

FIG.7

SPECIFICATION

A digital movement controller for automatic multi-axis machines

This invention relates to electronic circuits for the control of Robots and other automatic machines for the manipulation or machining of industrial components.

It is well known to control automatic machines by linear or analogue electronic circuits and these have traditionally had the advantage over digital circuits when applied in closed control loops, of giving adequately fast response times to handle the resonant frequencies, typically of up to 10 cycles per second, of the mechanisms controlled.
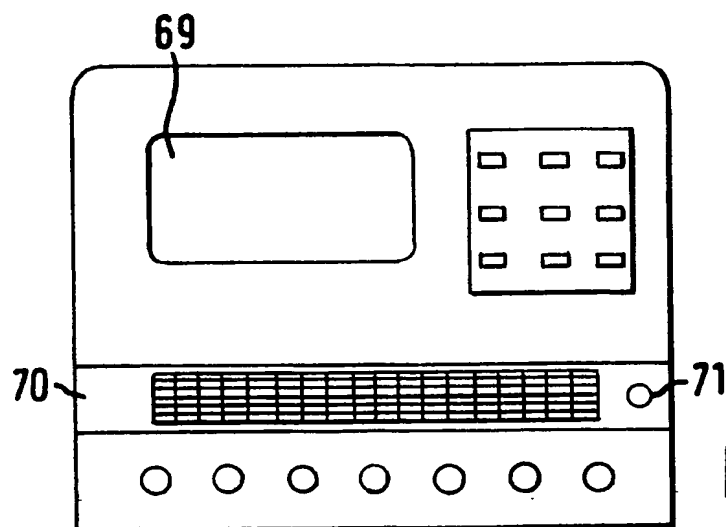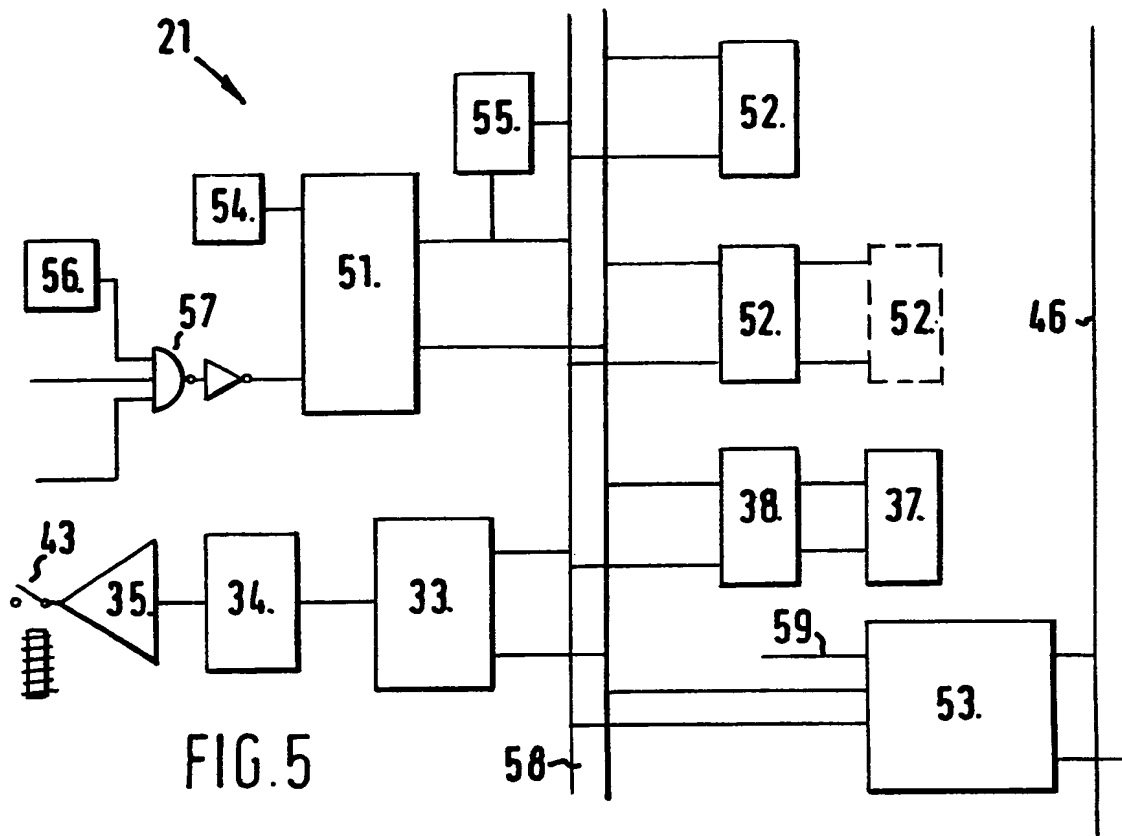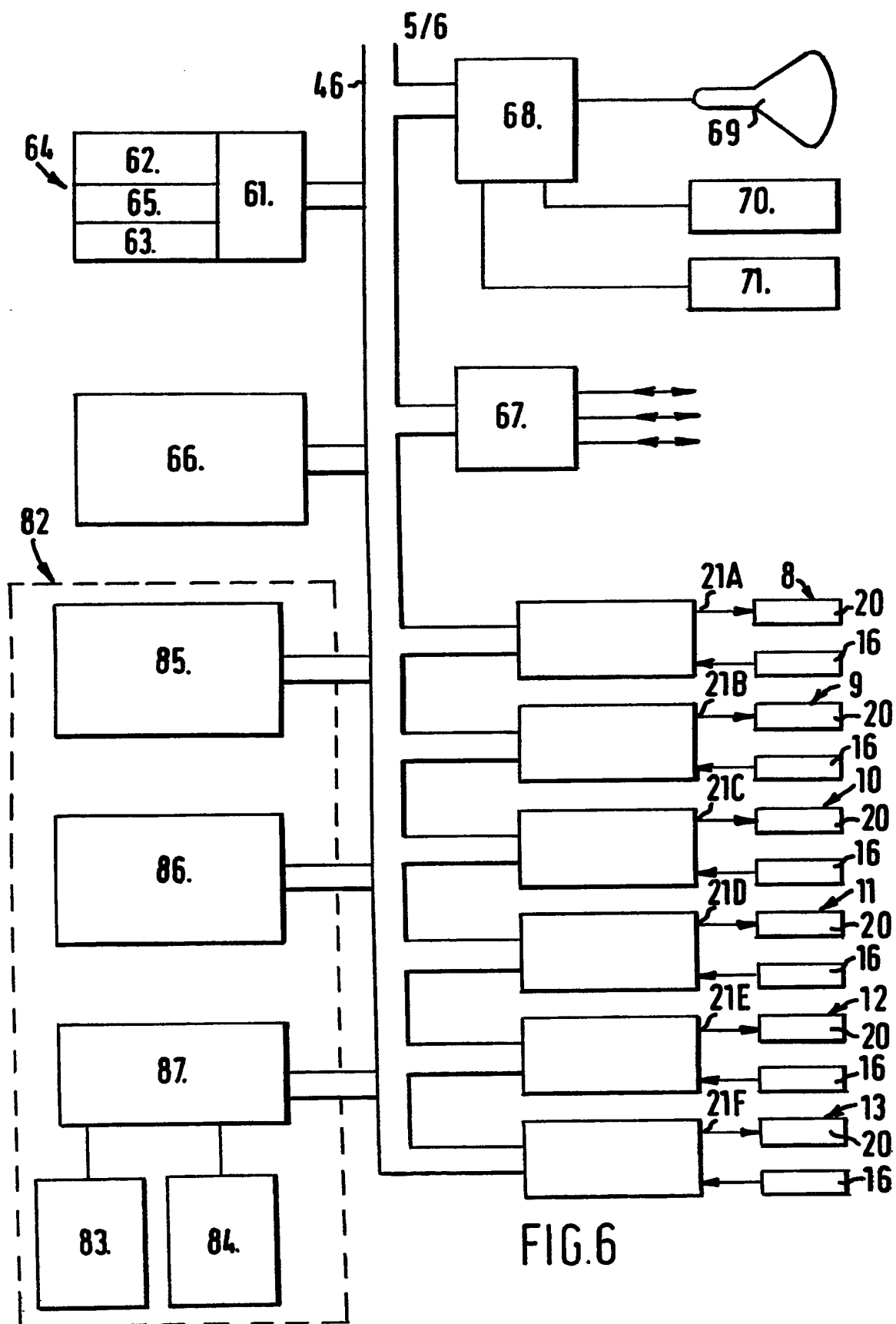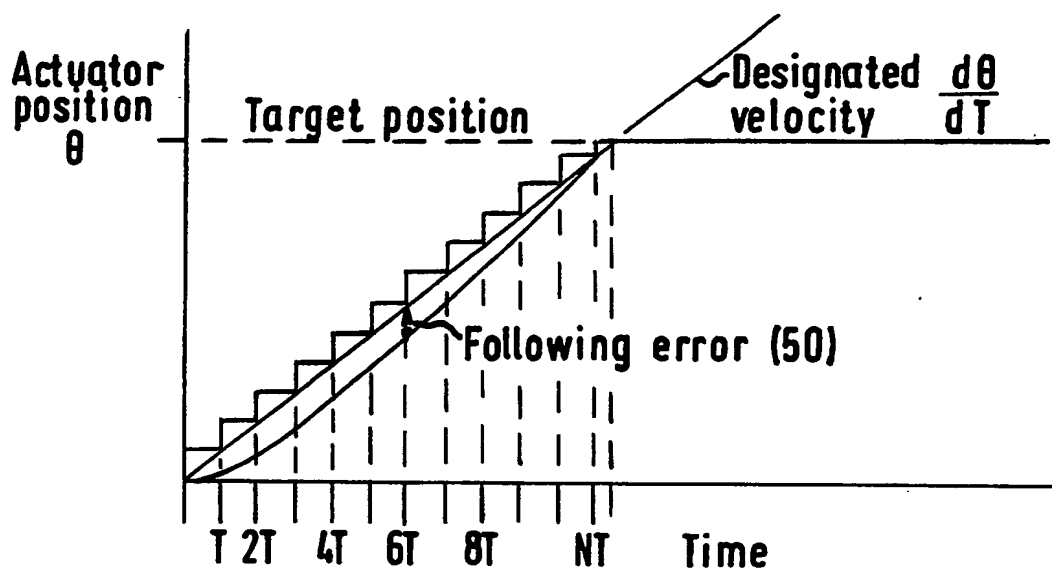
Digital circuits, however, offer the advantage of greater mathematical precision, and when such digital circuits are controlled by processors using stored programs, the further advantage of versatility is obtained.

The present invention combines the use of analogue techniques in the final drive circuits to the actuators of the controlled mechanism, with the mathematical precision of digital circuits and the versatility attainable with microprocessors without sacrificing speed of response.

More particularly the invention provides a control system for a multi-axis machine tool, welder, sprayer, robot or like mechanism in which the spatial position of the machine as a whole depends upon the contemporaneous positions of its several axes, wherein each axis is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move in a required direction and velocity during the next time period until the axis has reached its final target position and a central controller that supplies target positions to the several control modules through a common data highway to bring about required axis movements.

Hitherto, when using processors, economic considerations have dictated that the several axes of a multi-axis mechanism should share the services of a single processor(for example a minicomputer), but with complex multi-axis mechanisms that time-sharing introduces significant speed penalties.

Now that microprocessors are becoming more plentiful and of more modest cost, it has become feasible to use separate microprocessors to control each of the several interdependent axes and an additional common control microprocessor to coordinate the operation of the several axis controllers.

By this means, an adequate speed of response (typically 30 millisec.) can be ensured and sufficient spare processing capacity is available to facilitate the incorporation of further refinements only previously available in extremely complex and expensive systems.

The flexibility resulting from the use of a microprocessor in the control of each actuator makes it possible to design a standard printed circuit module which can be adapted by the provision of appropriate software, to match the required drive characteristics of a wide variety of integrating actuator mechanisms using hydraulic, pneumatic or d.c. motor drives.

While the immediate control of each actuator is effected by one dedicated printed circuit module, in a closed loop mode, depending on the feedback of positional data from an optical transducer associated with the controlled actuator, the overall control of the system and co-ordination of the movements of each individual actuator to produce a required overall movement of a workpiece or machine head, is vested in an additional controller module which itself comprises another printed circuit board equipped with its own microprocessor and associated memory circuits. Like the modules controlling individual actuators, the Controller module has high adaptable characteristics, so that the same assembly of Controller plus actuator control modules can be used to control a variety of automatic machines such as welders, robot handling devices, paint sprayers or machine tools.

To further facilitate the interfacing of the control system with a variety of existing and future machines and overall Production line control systems, the present system makes use of printed circuit boards, interconnections and power voltages consistent with current international standard recommendations.

To facilitate the initial setting up of machines, the definition of the required control parameters and for optional manual control, the system is provided with a comprehensive control panel comprising a cathode ray tube display, a series of programmable control keys and appropriate manual controls.

The number of actuators to be controlled is flexible, the basic cabinet provided having capacity to accommodate ten actuator control modules together with one Controller, the circuits associated with the control panel and the necessary power supplies. In a preferred application the system is used to control six actuators in a robotic work-handling device, the six axes in which the actuators operate being X, Y and Z with respect to a designated datum point, and "pitch", "roll" and "yaw" of the workpiece with respect to a designated angular orientation.

The invention will be understood from the following detailed description with reference to the accompanying drawings wherein:

Fig 1a illustrates the construction of a typical robotic arm, having six "joints" each controlled by actuators, and each having an optical transducer to feed back electronic signals to the controller and Fig 1b shows the construction of a typical joint;

Fig 2 represents in block schematic form, the fuctions provided by one of several identical axis control modules;

Fig 3 illustrates the input pulses supplied from an optical encoder to an axis control module, and the pulses employed in the module after pre-processing;

5   Fig 4a illustrates a typical transfer function for an actuator,

Fig 4b shows a correction function which may be applied in the axis control module to produce an ideal effective transfer function shown in Fig 4c;

10   Fig 5 represents in block schematic form the hardware units included in the axis control module, and their interconnections;

Fig 6 shows in block schematic form, the complete control system hardware, including the optional

15 maintenance module;

Fig 7 illustrates actuator position as a function of time and shows the correction of following error; and

Fig 8 illustrates the physical appearance of a pre-

20 ferred main control console forming the front panel of the cabinet housing the system hardware.

Figs 1a and 1b illustrate in diagrammatic form the structure of a robotic work-handling arm (1) which comprises six independent sections (2-7) intercon-

25 nected by joints (8-13) each of which is actuated in a rotary movement by a hydraulic actuator (16), while the resulting movement at each joint is monitored by an optical transducer, one of which (20) is shown coupled to actuator (16) in Fig 1b.

30   It will be appreciated that the effect of a given increment of angular movement at any one joint (8-13) will depend on the contemporaneous setting of all the other joints in the system. The analysis of the motion of any given actuator and its effect on the

35 position of the workpiece is therefore dependent on the position and movement of all the other actuators in the system. It is therefore desirable that the movement of each actuator be coordinated by a common controller module in which a microproces-

40 sor modules the behaviour of the entire structure and instructs individual modules (21) (referred to as axis control modules) for the several axes of joints (8-13) what increment of movement its actuator is required to execute next. The axis control module, which has

45 already been loaded with all the necessary data to enable it to interpret the received instructions and to convert these into relevant instructions to the actuator, takes into account all the idiosyncrasies of the actuator to which it is connected, which may

50 include oscillations, deformations under load, non-linear characteristics etc. and which are discussed in more detail below.

The absolute position and orientation of the work-piece (22) is calculated by the microprocessor in the

55 controller module from the data fed to it by indi-vidual axis control modules (21A-21F Fig 6) as movements are monitored in each joint (8-13). These movements are continuously monitored with the aid of the optical transducers (20) which in the machine

60 used to illustrate the invention, feed back to the axis control modules a pair of pulses for each increment of angle by which the joint moves. For the sake of this explanation it will be assumed that a resolution of 1 minute of arc is provided and that a pair of

65 pulses are output for each increment of angular

movement of this magnitude.

A type of optical transducer used in this kind of application outputs a pair of pulses shifted out of phase with each other by 25% of the repetition rate

70 for each of them. In other words, as the actuator turns in a clockwise direction, one pulse train leads the other by 90°, and when the actuator turns coun-terclockwise, the second pulse train leads the first by 90° in phase. This arrangement enables the associ-

75 ated electronics to distinguish between clockwise and anticlockwise motion of the actuator. These waveforms are illustrated in Fig 3a for clockwise rotation of the encoder.

The two trains of pulses described above are

80 shown passing from the optical transducer (20) to the Axis control module (21) in Fig 2, where they are interfaced to a CMOS directional logic circuit (23). This logic circuit generates two output pulse streams as illustrated in Fig 3b, one for clockwise movement

85 and the other for counterclockwise movement. The clockwise output from the directional logic circuit is applied to the clock input of a Counter/timer circuit (24) preferably of the type Z80CTC supplied as part of the Z80 microprocessor family of integrated cir-

90 cuits. This counter counts up to 255 and produces a corresponding 8-bit binary output before the most significant bit overflows and the counter reads zero on the 256th. pulse thus counting in modulo 256 without the need of a reset pulse. Similarly, the

95 counter-clockwise output from the directional logic circuit is fed to an identical Counter/timer circuit (25) which therefore counts the counter-clockwise pulses. The directional logic circuit (23) has a multi-plying effect and generates via monostable a well

100 defined pulse on both positive and negative going edges of both its outputs.

This increases the precision of the encoder feed-back by a factor of four. However, to synchronise closed loop operation an interrupt request pulse is

105 only generated on the positive going edge of the clockwise signals and output on signal line (48) by the directional logic circuit. In addition, this interrupt request can be enabled or disabled within the axis controller by a signal on input line (47) so that inter-

110 rupts can be prevented until the end of a calculation activity.

Typically this interrupt is enabled after 3ms, since this is the duration of the loop closure calculation process. During this time, if the actuator is moving, a

115 change in the accumulated count will have taken place, but the counter (24) will wait for the next posi-tive going transition of the clockwise phase before responding to the enable pulse (47) by outputting the interrupt request pulse (48). If the actuator is

120 moving slowly, the change in the accumulated count within about 3ms may be as little as 4 clockwise pulses. If the actuator is moving fast, there will be many pulses accumulated in 3ms (in multiples of 4), but the number will always be much smaller than

125 256, therefore there can be no ambiguity in the mag-nitude of the accumulated count.

The 8-bit binary counts from counter (24) and counter (25) are passed to the microprocessor where the counterclockwise count is subtracted (26) from

130 the clockwise count to produce a signed count of the

net change in angular position of the actuator as
sensed and signalled by the optical transducer (20).

One Megahertz clock pulses (ø), derived from a
crystal oscillator are divided down by a preset factor
5 N and by an additional fixed factor M in two cas-
caded Counter/timer circuits (17 and 18) type
Z80CTC to produce a series of timed Interrupt-Enable
pulses at equal predetermined intervals T, where T =
MxN microsec.
10   These pulses are shown along the time axis of a
graph relating actuator position θ and time in Figure
7.

The target position for the actuator (36) at the end
of the forthcoming move and the planned angular
15 velocity to reach that position, both expressed in the
form of 16-bit binary numbers, are loaded into the
buffer memory (53) shown, in Figure 5, by the central
control processor (61) shown in Figure 6.

When the Axis Control Module is ready to act on
20 the instructions in the buffer memory (53) its microp-
rocessor (51) shown in Figure 5 reads out the
intended angular velocity from the memory and cal-
culates the cumulative angular distances from the
prearranged datum, to which the actuator should
25 have moved at each of the times of the successive
Interrupt Enable pulses. The actual positions
reached by the actuator as defined by the signed
count output from stage (26) as described above, at
the moment of each interrupt pulse (output from unit
30 (24) on signal line (48) are compared in stage (27)
with the successive intermediate target figures for
the current and the next interrupt to calculate the
error to date and the distance to be covered in the
next time interval T. This determines the velocity
35 required to reach the correct position by the next
interrupt. This procedure is repeated until the calcu-
lated position for the next interrupt is beyond the
final target position, when the final target position is
substituted in the calculation for the normally calcu-
40 lated position.

This count is compared in stage (27) with the out-
put from stage (26) and also accumulated in stage
(27) to give a signal denoting the cumulative error to
date in the position of the actuator as compared with
45 its intended position.

Disregarding for the present, the calculations car-
ried out at stages (28, 29, 30, 31 and 32) the output
from stage (27) is passed to a Parallel Input/Output
Device (33) which is preferably the Z80PIO integrated
50 circuit forming part of the Z80 microprocessor set of
circuits. This device forms an appropriate interface
from the Z80 processor to a Digital to Analogue con-
verter (34). The analogue voltage output from this
converter is fed to an output amplifier module (35)
55 wholse output current is proportional to the input
voltage supplied to the amplifier from the D/A con-
verter (34), except in so far as an optional modifica-
tion has been built into module (35) to compensate
for any non-linear characteristics of the actuator (16)
60 which is driven by the output current from the amp-
lifier (35). The movement of this actuator continues
in subsequent intervals between interrupts, until the
destination co-ordinates of the workpiece have been
reached, and the optical transducer (20) continues to
65 monitor the movement of the actuator (36) through-

out the process.

A pair of cascaded counter/timers (37,38) similar to
those (14,15) alreay mentioned, are also clocked by
the crystal oscillator to give a further time reference.
70 This time reference is used in two further calcula-
tions by the microprocessor. The signed feedback
change output from calculation stage (26) is input
together with the time reference from timer (38) to
calculation stages (39) and (40). In stage (39) the
75 angle increment is divided by the time increment to
calculate the angular velocity, while in stage (40) the
angular velocity is further divided by the time incre-
ment to calculate the prevailing angular accelera-
tion.
80   The prevailing velocity calculated in stage (39) is
multiplied by a scaling factor "k$_v$" which has the
dimensions of time to produce an output with the
same dimensions (increments of angle) as the out-
put from stage (27). These last two mentioned quan-
85 tities are input to calculation stage (29) to derive a
difference, whose effect is equivalent to that of nega-
tive velocity feedback in an electronic hardware cir-
cuit, and therefore has a stabilising effect cancelling
out any tendency to oscillate on the part of the
90 closed loop circuit. Such tendency would be most
likely to occur as a result of mechanical resonances
in the actuator mechanism.

Factor "k$_v$" is adjusted to an optimum value to
minimise any such oscillation. The acceleration out-
95 put parameter from calculation stage (40) is similarly
applied to the output from calculation stage (29) in
calculation stage (30), in order to apply a similar
negative feedback stabilisation against any possible
second order oscillation effects which might remain
100 after the first stage of negative feedback had been
implemented in stage (29).

Four other optional adjustments will also be
explained at this stage, three of which may conve-
niently be implemented in software and the fourth in
105 hardware. Stage (28) is provided to enable offset
errors to be corrected. This type of error results from
physical distortion of the mechanical components of
the system when subjected to heavy loads, or more
probably in a hydraulic system, results when the
110 control circuits having correctly deduced that a cer-
tain rate of pumping oil into the hydraulic actuators
is called for to produce the remaining movement
necessary to take up the intended position, does not
know that the weight of the workpiece being lifted is
115 presenting so much resistance to the flow of oil into
the pump that the actuator is unable to respond as
expected. The offset error correction stage (28) has
been introduced to provide for the introduction of a
further step function of lift to compensate for this
120 "sagging" effect produced by a heavy workpiece.
The magnitude of the correction to be made is
measured when the workpiece is stationary.

Stage (31) provides for the input of a non-linear
gain factor to compensate for the non-linear transfer
125 function frequently encountered in the operation of
hydraulic and pneumatic actuators. If, for example,
there is a dead spot near the unactivated position of
the actuator, and if the sensitivity for forward motion
is different from that of backward motion, as is often
130 the case, a typical transfer function for an actuator

may be as in Fig 4a in which input current is plotted
against movement. If then the adaptive gain applied
at stage (31) has the form shown in Fig 4b, the com-
bined effect of these two factors will result in the
5 linear overall transfer function shown in Fig 4c, with
a correspondingly better dynamic performance.
Stage (32) is provided to enable a controlled oscilla-
tion or "dither" to be introduced into the control
loop. It is well known that a small amplitude vibra-
10 tion applied to a mechanical mechanism will minim-
ise the effects of static friction by substituting
dynamic friction, which is generally lower by a sig-
nificant factor. Instead of introducing this as a physi-
cal vibration, the same effect can be achieved by
15 introducing a controlled "dither" at a suitable fre-
quency and amplitude into the control loop. It has
been found, in the preferred embodiment, that a
square-wave signal at a frequency of 80Hz intro-
duced into the digital count output from stage (31) at
20 stage (32) and before application to the parallel
input/output stage (33) is effective. The 80Hz fre-
quency is conveniently derived by counting down
from the basic clock frequency in another
counter/timer circuit (not shown in Fig 2) and its
25 amplitude is defined in stage (42).
   The adaptive gain control software module (31)
may involve a fairly complex calculation, and under
certain conditions the time taken for this calculation
could limit the speed of response of the rest of the
30 control loop. For conditions when this might be of
critical importance, an option is available whereby
this function is provided in hardware as shown in Fig
2 at hardware module (41). This would perform the
same function as has already been described above
35 for software module (31), but much more rapidly.
   A relay (43) is used as a breaker in the circuit bet-
ween the current amplifier (35) and the actuator (36).
This ensures that the control loop can be broken in a
fail safe fashion in the event of a power failure or any
40 other circumstances calling for an "Emergency
Stop". Interruption of the actuator drive by this
means causes the mechanism to stop moving and to
remain in its current position until the drive circuit is
restored.
45   The output from amplifier (35) is a d.c. current
nominally proportional to the analogue input to the
amplifier. This is one form of drive required by integ-
rating hydraulic actuators connected to electrically
controlled valves which produce a response propor-
50 tional to the output current. For d.c. motor applica-
tions where it is required to produce a voltage out-
put, this is readily arranged by applying the output
current to a load resistor, or by other means.
   The error offset correction applied in stage (28)
55 comes into operation only when the workpiece is
stationary at the end of a programmed movement. It
is only appropriate to apply it after the more conven-
tional effects of time-lag in the attainment of the final
position have been accounted for.
60   By synchronising the interrupt requests from
counter (24) to one edge only of the clockwise output
pulses, a high precision in the timing of the interrupt
is achieved, which is reflected in the accuracy of the
time intervals to 1 microsec. in 3 milliseconds, or for
65 longer time intervals, the limit is set by the 1 part

65,000 count limit of the timing counters. In addition
the accuracy of position resolution can be increased
when required by means of an optional alternative
mode for synchronising the interrupt requests to any
70 of the four pulse edges of the outputs from counters
(24,25). By this means it is possible to improve the
angular resolution available by a factor of four. This
is greater than is normally required. It can be
implemented by means of a keyboard command on
75 the control panel (70), and is normally only used
when setting the initial datum positions for a
machine.
   It is found that the calculated velocity and acceler-
ation signals through the stages (39 & 40) can be
80 subject to random fluctuations, and therefore it is
found expedient to provide these stages with digi-
tal filtering algorithms in which successive
smoothed values of velocity and acceleration (v_{ns},
A_{ns}) are derived from the previous smoothed values
85 ($v_{(n-1)s}$, $A_{(n-1)s}$, by simple calculations of the form:

$$v_{ns} = \frac{K \cdot V_{(n-1)s} + V_n}{K+1}$$

90
$$A_{ns} = \frac{K \cdot A_{(n-1)s} + A_n}{K+1}$$

where V_n, A_n are the current raw inputs, and V_{ns}, A_{ns}
the corresponding smoothed values. The factor K
may be set as required to give an optimum time
95 constant. A preferred value of K is 3.
   The loop gains k_v and k_a in stages (44) and (45) can
also be set up by keyboard instructions. It is also
possible to disable, i.e. open, these loops from the
keyboard when required.
100   The complete hardware content of an Axis control
module (21) is shown schematically in Fig 5, includ-
ing the Z80 microprocessor (51) and its supporting
memory modules (52).
   The interface logic and RAM module (53) provides
105 256 bytes of storage, part of which is used as a buffer
between the Axis Control module and the central
controller.
   Forty eight bytes of data arranged in three blocks
of 16, are used to communicate control parameters
110 from the controller to the axis control module and
for the interchange of target actuator positions (from
Controller to Axis module) and of monitored actual
movement towards those positions (from Axis Mod-
ule to Controller). The actual allocation of the bytes
115 within the three blocks for a typical application is
illustrated in Table 1. When the actuator controlled
by an Axis Control Module has reached the final
target position, it signals to the central Controller
with an interrupt.
120   At any time during the progress of the actuator
towards its final position, the controller has access to
the buffer (53) and can compare the actual position
reached at the last interrupt with the intended posi-
tion, and can compute the following error (50). Sub-
125 sequent instructions to the axis Control Module may
be modified to correct this error.
   Communication between the central controller
and the Axis Control Modules is over an Industry
standard 86-conductor communication highway (46)
130 as shown in Figure 5. The several Axis Control Mod-

ules (21) all share common signalling lines, their
interface buffers (53) being loaded from and interro-
gated by the Central Controller on a priority interrupt
basis.
5 One of the inputs available on the Z80 microp-
rocessor is a non-maskable input. This is used to
initiate a non-maskable shut-down routine. Three
inputs are provided to the NAND gate (57), allowing
an internal POWER FAIL logic level, a POWER FAIL
10 signal directly from the Power Supply, (56) or a
signal from the EMERGENCY STOP button (71) to be
used.
The timing signals to the Z80 processor are pro-
vided by a conventional clock pulse generator mod-
15 ule (54). Internal communication between the units
comprising the Axis Control Module is over an inter-
nal Z80 data bus (58).
Interrupts to the Interface logic (53) may be initi-
ated either over the external multibus highway (46)
20 or from the Axis Control board itself on input line
(59).
Fig 6 illustrates in block schematic form the com-
plete system according to the invention, including
six axis-control modules (21A – 21F) all of which are
25 identical and, as described above, are used to drive
six actuators (8-13).
The central processor (61) used in the controller is
a type 8080 microprocessor. It is assembled on a
printed circuit board (64), together with an Arithme-
30 tic unit (62) and the PROM and RAM memory units
(63,65) intimately concerned with its basic operation.
One of the principal operations carried out by the
Arithmetic unit (62) is a conversion from cartesian to
polar co-ordinates as required to instruct the axis
35 control modules (21) what angular movements are
needed from their respective actuators to implement
the required movement of the workpiece in three
cartesian dimensions. The Arithmetic unit consists
of a microprocessor chip with an efficient perfor-
40 mance in the cartesian to polar transformation. In
particular it is capable of calculating trigonometric
functions vary rapidly and accurately.
The optimum movement of the workpiece bet-
ween its initial and final positions is usually in a
45 straight line and therefore, when the system is prog-
rammed in cartesian mode, the algorithms used are
those which best meet this criterion.
When it is opportune, or necessary to instruct the
machine to move the workpiece via a complex route,
50 for example to avoid an obstruction, manual prog-
ramming can be used, teaching the necessary prog-
ram to the machine step my step from the keyboard.
The central processor (61) communicates over
highway (46) with a memory module (66) and with
55 an input/output module (67).
The input/output module (67) provides for opti-
cally isolated data communication with external
modules such as relays, contactors, etc. on other
machines with which the operation of the robot must
60 be interlocked.
The CMOS RAM memory card (66) is provided
with its own small rechargeable battery wired onto
the card to enable data to remain stored therein
when the power supply to the rest of the system has
65 been switched off. Due to the low power consump-

tion of CMOS RAM devices, data can be retained in
this memory for one month without the battery
being recharged.
A further module sharing access to the common
70 highway (46) is the control module (68) for a Visual
Display (69), and keyboard (70). Some of the controls
on the keyboard may be extended for remote opera-
tion by an appropriate Remote Control Unit (71).
The touch-sensitive keys on the main program
75 keyboard (70) may be programmed to meet the
requirements of any particular application, being
similar in format to the keyboard of a conventional
visual display terminal. A typical layout of this
keyboard is shown in Fig 8. The Cathode Ray Tube
80 (69) may be used to display alphanumeric data input
from this keyboard, or tabulated data derived from
the axis modules or the central controller.
The predetermined control software for the sys-
tem is provided in PROM form, and the variable
85 parameters entered from the keyboard are held in
the battery backed RAM modules (66). When it is
necessary to generate a new program, or when
diagnostic routines are called for, a special mainte-
nance module (82) can be plugged into the system.
90 This module includes a floppy disc driver (83), an
additional visual display (84), a dynamic RAM mod-
ule (85) and a PROM programmer (86).
Maintenance routines, or any other development
software, may be stored on floppy discs and loaded
95 via the disc drive module (83) to the RAM module
(85) and thence used to control the system. The disc
module is controlled by disc controller (87). Modifi-
cations to a program may readily be made when it is
held in this RAM module, using the controls on the
100 main control keyboard (70). Once a new program
has been compiled and debugged, it can be transfer-
red from this RAM onto a PROM using the PROM
programmer module (86).
For the convenience of maintenance engineers,
105 the maintenance module (82) is easily portable.
The complete system therefore consists of the
System Processor Card (64), the Memory Card (66),
the Keyboard/CRT control card (68), the Input/Output
card (67) and sufficient Axis control cards (21) to
110 drive the number of axes used on the controlled
machine. In the preferred embodiment described the
number of axis cards is 6, but there is accommoda-
tion provided in the cabinet, and in the multiplexing
arrangements for ten axes to be served. In principle,
115 the system may readily be extended to serve more
than ten axes.
All the axis control cards are identical, even the
preset adjustments appertaining to the properties of
the different actuators in a system are implemented
120 by software in the main controller, so, in the event of
a malfunction in any axis module, a spare axis mod-
ule can be fitted in its place and no adjustments are
required before resuming operations.

TABLE 1: *AXIS CARD DATA BLOCK STRUCTURE*

	MOVE DESCRIPTION	COMMON MOVE PARAMETERS	CONTROL LOOP PARAMETERS
0		STATUS	
1		CONTROL	
2	LS TARGET	LS ALLOWED MAX ERR ERROR	FACILITIES ENABLE FLAGS
3	MS TARGET	MS ALLOWED MAX ERROR	MANTISSA GAIN (+DIR)
4	LS VELOCITY	ACCELERATION LIMIT	EXPONENT GAIN (+DIR)
5	MS VELOCITY	DECELERATION LIMIT	MANTISSA GAIN (−DIR)
6	LS INT DIST	MS VELOCITY LIMIT (LS = 0 IMPLIED)	EXPONENT GAIN (−DIR)
7	MS INT DIST	LS POS POSITION LIMIT	MANTISSA VELOCITY LOOP GAIN
8	LS MAX ERROR FOUND	MS POS POSITION LIMIT	EXPONENT VELOCITY LOOP GAIN
9	MS MAX ERROR FOUND (FIGURE OF MERIT)	LS NEG POSITION LIMIT	MANTISSA ACCELERATION LOOP GAIN
10	ERROR CODE	MS NEG POSITION LIMIT	EXPONENT ACCELERATION LOOP GAIN
11	SPARE	LS AXIS IN POSITION THRESHOLD (MS = 0 IMPLIED)	FUNDAMENTAL TIME UNIT
12	SPARE	LS AXIS STOPPED VELOCITY THRESHOLD (MS = 0 IMPLIED)	LS DITHER AMPLITUDE
13	SPARE	LS DATUM OFFSET	MS DITHER AMPLITUDE
14	SPARE	MS DATUM OFFSET	SPARE
15	SPARE	SPARE	SPARE
	BLOCK A	BLOCK B	BLOCK C

CLAIMS

1. A control system for multi-axis machine tool, welder, sprayer, robot or like mechanism in which the spatial position of the machine as a whole depends upon the contemporaneous positions of its several axes, wherein each axis is moved by an actuator and its movement is monitored by a transducer electrically connected to an individual control module including digital data processing means that repeatedly determines the distance through which the axis has moved, compares the position of the axis with an interim target position and supplies a control signal to the actuator to cause it to move in a required direction and velocity during the next time period until the axis has reached its final target position and a central controller that supplies target positions to the several control modules through a common data highway to bring about required axis movements.

2. A control system according to Claim 1, wherein the transducer means is arranged to supply an electrical signal to a directional logic circuit in the control module that produces clockwise and anticlockwise outputs which are supplied to individual counter circuits, and arithmetic means arranged to substract one count from another to produce an output denoting the magnitude and direction of the change in angular position signalled by said transducer means.

3. A control system as claimed in Claim 1 or 2, wherein each control module further includes means for calculating the velocity of the joint, the output of which is used to give a negative feedback component to the signal to the actuator to reduce oscillations thereof.

4. A control system as claimed in Claim 3, wherein each control module further includes means for calculating the acceleration of the joint, the output of which is used to give a negative feedback component to the signal to the actuator to reduce oscillations thereof.

5. A control system as claimed in any preceding claim, wherein each control module further includes means arranged to adjust the control signal to the actuator to compensate for sagging of the arm resulting from the weight of a workpiece that it carries.

6. A control system as claimed in any preceding claim, wherein each control module further includes means arranged to provide a correction to the control signal to the actuator to compensate for nonlinearity in the transfer function thereof.

7.   A control system as claimed in any preceding claim, wherein each control module has means arranged to inject a "dither" component of cyclically varying amplitude into the signal supplied to the
5 actuator at such a frequency and amplitude as to substitute dynamic friction of the respective axis for static friction.

8.   A control system as claimed in any preceding claim, wherein the components of each control
10 module are mounted on a respective individually removable printed circuit board.

9.   A control system as claimed in any preceding claim, wherein the central controller is arranged to signal target positions to the several control mod-
15 ules at intervals, the several control modules are arranged to signal to the central controller at intervals how far the position of the respective axis differs from the target position after that interval and the central controller is arranged to supply updated
20 control signals to the several control modules for the next interval.

10.   A control system as claimed in claim 9, wherein the several control modules communicate with the central controller in time division multiplex.
25 11.   A control system as claimed in any preceding claim, wherein the transducer is an optical encoder.

12.   A control system for a multi-jointed arm or the like substantially as hereinbefore described with reference to and as illustrated in the accompanying
30 drawings.